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Walking and Teleportation in Wide-area Virtual Reality Experiences

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Figure 1: User shown in both our real wide-area study environment (roller hockey rink) and virtual environment with gem target.

Abstract

Location-based or Out-of-Home Entertainment refers to experiences such as theme and amusement parks, laser tag and paintball arenas, roller and ice skating rinks, zoos and aquariums, or science centers and museums among many other family entertainment and cultural venues. More recently, location-based VR has emerged as a new category of out-of-home entertainment. These VR experiences can be likened to social entertainment options such as laser tag, where physical movement is an inherent part of the experience versus at-home VR experiences where physical movement often needs to be replaced by artificial locomotion techniques due to tracking space constraints. In this work, we present the first VR study to understand the impact of natural walking in a large physical space on presence and user preference. We compare it with teleportation in the same large space, since teleportation is the most commonly used locomotion technique for consumer, at-home VR. Our results show that walking was overwhelmingly preferred by the participants and teleportation leads to significantly higher self-reported simulator sickness. The data also shows a trend towards higher self-reported presence for natural walking.

Index Terms: Human-centered computing—Interaction paradigms—Virtual reality;

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1 Introduction

Since the early days of virtual reality (VR), the consumer market has been a major focus of the field. With the introduction of cheaper and more capable devices in recent years, consumer VR has continued to gain popularity and is now increasingly inspiring creators to integrate VR in entertainment experiences in innovative ways. For example, amusement parks offer VR roller coaster rides [47], entire theme parks are dedicated to VR [19], and chefs in New York City host culinary experiences that incorporate VR [27]. Location-based VR has emerged as a new category of entertainment with venues set up in warehouses or existing malls and movie theaters. Companies create bespoke high-end experiences [15, 45] where groups of people roam freely in large physical spaces. While location-based VR setups vary and can utilize a wide range of tracking spaces from 5x5m rooms in Dreamscape [15] to much larger warehouse-sized spaces in The Void [45], in this work we consider tracking spaces larger than 10x10m as wide area. Real walking is a primary form of locomotion in these experiences. Sometimes, the VR space size requirements are constrained by physical space size, layout, and obstacles. If a large open tracked interaction space is available for wide-area VR, VR environments can flexibly be layered on top of the physical space.

A compelling use case for virtual and augmented reality (AR) deployed in wide-area environments is the possibility of storytelling for educational and entertainment purposes in the physical world. Location-based AR applications such as Pokémon Go have already shown tremendous success. With a few more technological advancements, one could imagine creating *immersive* narratives similar to theme parks anywhere without the theme park infrastructure. Immersive AR content could seamlessly transition to immersive VR content depending on the type of physical space a user walks through. We are interested in exploring the technical and cognitive feasibility and side effects of such scenarios. In pursuit of these future pos-

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sibilities, we present what we believe is the first study evaluating cognitive impact of real walking in VR over wide-area spaces. Prior work has explored real walking in wide-area VR, in both indoor and outdoors spaces. Hive [46] is a 570 m^2 indoor space tracked with an outside-in World Viz PPT X8 tracking system. The virtual environment is rendered on backpack-worn computers to enable mobility in the tracking space. In contrast, VRoamer [10] uses a head-mounted device with inside-out tracking to dynamically generate virtual elements in ways that allow users to safely walk in indoor spaces. DreamWalker [51] is a system for walking to a pre-defined real world destination while staying fully immersed in VR with pathfinding and obstacle avoidance in a pre-authored VR environment. Though some of these works include user studies to validate the design aspects of the system, there remains a gap in the literature on studying the effects of walking in wide-area VR on presence, simulator sickness, and cognitive map building. There has also been limited research on comparing natural walking and teleportation in these domains. Teleportation has been compared to joystick based movement [7, 23] and other forms of locomotion in room-scale VR. Similarly, natural walking in small environments has been compared to multiple forms of joystick control with respect to several aspects of cognition [52]. Our work aims to address this gap by comparing wide area natural walking with teleportation for presence, simulation sickness, cognitive map building, and user preference.

The benefits of supporting natural body movement have been extensively studied in VR. For example, walking has been shown to result in higher self-reported presence than walking-in-place and joystick based locomotion [43]. Walking has also shown superior performance on search tasks [30] with benefits for spatial orientation [8] and attention [39]. Despite well-known advantages of walking in VR, it is not often employed in room scale experiences because a direct mapping of physical walking to virtual motion makes it impossible to reach virtual spaces that fall outside of the boundaries of the physical tracking space [41].

Since walking in VR has been studied since the mid 90s, it is not very surprising that some study results are contradictory. We believe the differences are probably due to the studies being conducted in different decades with different hardware and virtual environments. For example, in 1999 Usoh et al. [43] showed walking to elicit higher presence than walking-in-place or flying in an indoor environment of 5x4m, while in 2005 Zanbaka et al. [53] found no differences in simulator sickness between real walking in a small room and several virtual travel techniques, and in 2009 Suma et al' [40] showed walking to cause high motion sickness in a complex maze environment [40].

For location-based VR, walking is the primary form of locomotion, while teleportation tends to be the primary form for room-scale VR experiences. Both primarily stem from tracking space availability, though location-based VR experiences are also co-located social VR experiences [15, 45] for which walking works better than teleportation. As each locomotion technique varies in its usability, influences the user's sense of presence differently, fatigues the users to varying degrees, and elicits different levels of motion sickness, it also has a different impact on virtual task performance [30].

Most of the previous comparative studies on natural walking use joystick control as an alternative interface. In a more recent study [7], Buttussi et. al. showed that a point and teleport interface can be superior to joystick control with regard to simulator sickness, presence, and ease of use. We chose point and teleport as our comparison locomotion technique. In this work, we explore natural walking and teleportation in a wide-area space to understand their influence on presence and cognitive map building. Walking in large physical spaces has only recently become affordable, due to the availability of standalone VR headsets such as the Lenovo Mirage Solo or the Oculus Quest that have built-in inside-out tracking.

To the best of our knowledge this is the *first comparative study of natural walking in a wide-area VR experience*. We compared a variety of metrics against controller-based point and teleport. We also investigated the transfer of previous findings about real walking both to wider areas and to state-of-the-art lightweight mobile VR headsets in high-fidelity outdoor and indoor virtual environments.

We encouraged scene exploration via an object collection task and compared *virtual scene coverage* and *mental map formation* through a series of pointing tasks after exploration. We also assessed *user preference*, and administered *presence* and *simulator sickness* questionnaires.

Our results provide insights into the effects of walking and teleportation in wide-area VR experiences. They indicate decided *advantages of natural walking over teleportation* in wide-area VR in terms of user preference and induced disorientation with some indications of better mental map formation.

2 Related Work

Here we discuss related prior work in three categories: locomotion in AR/VR, redirected walking and spatial cognitive map building.

2.1 Locomotion in AR/VR

Navigation is a universal task performed in both real and virtual environments [5]. AR users can easily navigate and avoid obstacles as the world is visible through AR displays. Games like Pokémon Go [26] and Human Pacman [11] are successful examples that enabled interaction with virtual objects while moving in the real world with high levels of enjoyment and sensory gratification. However, research shows risks of injury even when the physical environment is visible [32]. This risk is multiplied in VR when the physical world is not visible.

Walking in VR has been desirable due to its ease of use [30] and its ability to elicit higher presence compared to other techniques like walking-in-place or flying [43], and joystick based locomotion [23]. However, effectively navigating VR environments without provoking VR sickness continues to be a major obstacle for VR development [37]. A lot of research has focused on creating novel techniques to enable walking in room scale setups, such as redirected walking [29], resetting [49], or perceptual illusions in VMotion [33]. However, these techniques are not yet commonly available in at-home VR experiences as they require at least some tracking space for the user to move. For example, VMotion requires the user to have at least a 4x4m space while for curvature gain to remain undetected, the circular walking arc needs to have a radius of at least 22m [35]. More recent work shows that users can be redirected on a circular arc with radius of either 11.6m or 6.4m depending on the estimation method used [18] As a consequence of tracking space limitations, teleportation has become the most commonly used locomotion technique in room scale VR experiences [4].

The most basic form of teleportation involves the user pointing a controller towards a position in the virtual world and clicking a button to instantly move there [6]. Since it discontinuously translates the viewpoint, instant teleportation does not generate any optical flow, and thus reduces the risk of vection induced VR sickness [2, 12, 14, 17]. However, this beneficial reduced VR sickness comes with an increase in disorientation and break in presence [50]. To address this many variations of teleportation have been proposed that each show improvement in certain aspects. For example, the scene blinks to blackness momentarily as one moves to a new location in Blink [13]. Or in Telepath [1], users move smoothly along a hand-drawn path at walking speed. In Dash [2], user viewpoint is discontinuously but rapidly translated to the point of interest which leads to better path integration.

2.2 Redirected Walking

Redirected walking allows users to walk naturally in virtual worlds through continuous manipulation of mapping between physical and

(a) Indoor Virtual Spaces (b) Outdoor Virtual Spaces

Figure 2: (a): Indoor virtual spaces, which are two adapted halves of the same Matterport 3D dataset model. (b) Outdoor virtual spaces, created by authors in two different shapes.

virtual rotations that steer the user away from the tracking space boundaries [29]. To overcome tracking space limitation, a number of redirection techniques have been proposed that manipulate the user's perceived self-motion such as translation [21, 48], rotation [35], or curvature gain [25], motion compression [36], and virtual scene manipulation such as portals [34], saccadic redirection [42], and non-Euclidean geometry [41] to enable walking in the larger virtual area without exiting the smaller tracking area. All of these techniques either rotate the virtual world or scale the user's motion to allow them to cover more virtual ground. They typically require a large physical space [35] or have difficulty changing a user's direction when the user gets close to tracking space boundaries [38], and are thus somewhat limited in their use in consumer applications. Reorientation or resetting is a class of techniques that stop and reorient the user when they are close to the boundary of the tracking space, unlike redirection which is applied continuously. Williams et al. [49] proposed reset techniques that direct the user to walk backwards or to physically turn around while the virtual world remains frozen. As resetting interrupts the natural walking experience, it may decrease the user's sense of presence. To mitigate disruption, VMotion [33], combines the perceptual illusion of inattentional blindness with various visibility control techniques to mask the virtual world rotation by engaging the user in the story.

2.3 Cognitive Map Building

People learn the spatial layout of new environments (locations, distances, directions) relatively quickly and acquisition begins as soon as they arrive in a place [24]. They create a world-reference frame for the layout representing the environment in an allocentric form also called a cognitive map, survey knowledge, mental model, or mental map [31]. Peck et al. [28] compared redirected walking to walking-in-place and joystick for navigational ability (i.e., the performance during a search task) and reported that participants "traveled shorter distances, made fewer wrong turns, pointed to hidden targets more accurately and more quickly, and were able to place and label targets on maps more accurately" when using redirected

Figure 3: Gem collection and Teleportation tool, both visible on the controller. Users pressed the touchpad button to teleport to the white spot. They pressed the second button on the controller while pointing the 'laser beam' at the gems (metallic icosahedron) in order to collect them. The UI on the controller kept track of the number of gems collected.

walking. Langbehn et al. [23] also showed that redirected walking better enabled users to unconsciously acquire spatial knowledge about the virtual world than teleportation or using a joystick. In another study where portals were used to reorient the user, teleportation was compared to joystick and walking through portals [16] and was found to be faster than walking, but worse than joystick for determining orientation. Proprioception and translational body-based information was found to significantly improve navigational performance and accuracy of cognitive maps [30, 31]. Since walking provides proprioceptive information and is inherently translational, it should help in better cognitive map building than non-translational locomotion techniques like teleportation, and this forms the basis of our experiment.

3 Formative Experimentation

We used the Lenovo Mirage Solo VR headset with inside-out tracking and a 3DOF handheld controller and Google VR SDK for Unity for the experiment. By default, for safety, the device fades to black if the user moves around more than 1m, a measure that we disabled in developer mode to allow for walking large distances. The SDK, however, does not provide access to the localization and mapping process, so it was not possible for us to tune or improve the tracking programmatically. Therefore, we needed to find, by trial and error, physical locations with favorable tracking conditions, to run a wide-area walking experiment.

We tested several outdoor areas at different times of the day to determine where our device's tracking system would work best. While tracking worked intermittently in all these spaces, outdoor dynamic lighting proved to be problematic. Even though most of our testing was done during the day in shady spots or close to dusk, we damaged the display on one device due to accidental exposure to sunlight when transporting the device to the test site. Lighting also changed dramatically during the hour of the experiment, causing uneven tracking performance. The inside-out tracking would also fail often as there were fewer distinct texture features in these wide area spaces than necessary for tracking to work seamlessly. We conducted tests in a baseball field, a soccer field with floodlights, on a grassy campus quadrangle, and on a marked track and field area. While we expected tracking to work due to sufficient texture, field markings and other such features, it failed repeatedly, most likely due to the self-similarity of grass and ground textures and

Figure 4: Blending in the real environment on the periphery to help users avoid physical obstacles. This technique was not used in our final walking experiment, but is an interesting option in smaller spaces.

other landmarks being too far away to create sufficient parallax.

We experimented with a mixed-reality locomotion technique in which we would fade in the camera feed from the headset into the user's peripheral vision each time they started moving and fade back to full VR view when the user stopped and simply looked around (see Figure 4). Pilot users testing this interface successfully maintained focus on the virtual environment and felt immersed even while walking and seeing the real world in their periphery. While this technique creates an effective AR + VR interface in a single device, it also introduces differences for different users and different scene explorations, as users would see the physical world shining through at different times.

The lighting and tracking issues led us to test indoors in a few different basketball courts and gyms on our campus, and in those environments there was no risk of bumping into obstacles or stumbling on uneven ground. Therefore, we didn't end up employing this technique for our experiment in the end, but it is a compelling UI for eventual deployment of wide-area VR walking.

4 Experiment

In this experiment, we analyze the effects of two locomotion techniques, namely, natural walking and instant teleportation, on cognitive map building in VR. We also consider other aspects of virtual experiences, such as motion sickness, sense of presence, and user preference of the locomotion technique.

Instant teleportation is a point-and-click mechanism that does not require the user to physically move while allowing them to change their virtual location instantly. It can be implemented easily for commodity VR setups without any additional bulky equipment and is included by default with the primary VR plugins like SteamVR for Unity3D. As mentioned before there are many variations of teleportation with varying benefits for minimizing user discomfort. We chose this basic implementation for our experiment as it was the most used interface in the previous studies. In our implementation, the controller touchpad button is pressed down and held and the teleportation destination is indicated by a ray followed by a circular marker on the ground (see Figure 3). Instant movement to the destination is accomplished by releasing the touchpad. The visual leap can cover both short and long distances as long as the user is able to point and place the circular marker on the virtual floor plane. This means the user can go from one end of a large virtual environment to the other end in an instant, if there are no walls

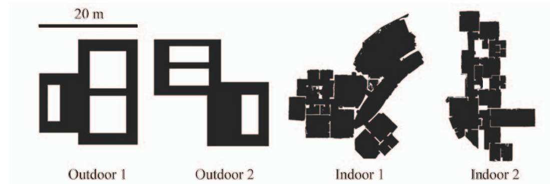

Figure 5: Top-down view of the outdoor and indoor environments.

in between blocking their line of sight. The user's initial body orientation determines their arrival orientation at the destination.

The experiment was conducted in an indoor roller hockey rink of size 61m x 26m (NHL regulation size) that was prepared for robust 6DoF tracking with our VR headset with the inclusion of extra ground texture as described below in 4.2 (see Figure 1). Based on dominant results from prior work in room-scale VR that have shown walking to perform better than other techniques on presence, spatial mapping and motion sickness, we defined the following hypotheses:

- H1: Natural walking will provide better spatial layout information than teleportation.
- H2: Teleportation will induce higher disorientation, except when inside-out tracking fails in natural walking.
- H3: Natural walking will provide a higher sense of presence than teleportation.

4.1 Participants

We recruited 16 participants (7 male and 9 female) with an average age of 19. Most of them were students or employees of our university as we recruited on campus. 10 participants had at least some experience with VR with the mode being 1 and mean of 2.0 on a scale of 1 (no experience at all) to 7 (very experienced). The total time per participant, including pre-questionnaires, instructions, in-study tutorials, experiment conditions, and post-questionnaires was 1.5 hours. Each study was conducted in a single session and participants were compensated at the rate of 15 USD per hour. Participants wore the headset for 5 minutes per locomotion condition and navigated through two indoor and two outdoor virtual spaces during the experiment. Participants also went through two tutorials, two minutes long each. The study was approved by our university's office of research and all participants provided informed consent. Participants were given instructions on how to perform the experiment tasks before starting the experiment. They were asked to pay attention to their virtual surroundings during their exploration. Before starting, participants filled out a demographic questionnaire about their experience with gaming and VR along with the Santa Barbara Sense of Direction questionnaire (SBSOD) [20] and the Kennedy-Lane Simulator Sickness questionnaire (SSQ) [22].

4.2 Apparatus

Our final experiment was conducted in the aforementioned indoor sports arena, with 61m x 26m of open walkable area on campus using the Lenovo Mirage Solo VR device. To increase the accuracy of the headset's inside-out tracking system, we placed several additional markers (newspaper and other printed material) on the ground to augment the tracking environment with extra features. With these preparations, 6DoF tracking of our participants performed reliably most of the time. Participants wore noise cancelling headphones to follow verbal instructions in the two tutorials and kept wearing them during the experiment. Noise cancelling headphones were used to help reduce the natural environment noise in the university recreation center (see Figure 6).

Figure 6: View of the tutorial environment. Users spawned in this environment and were provided with prerecorded interactive instructions on how to use the interfaces. This included teleportation/walking, collecting the gems and answering the pointing questions. The green glowing spot is shown to ask the user to teleport to that location. Users were verbally instructed through their headphones.

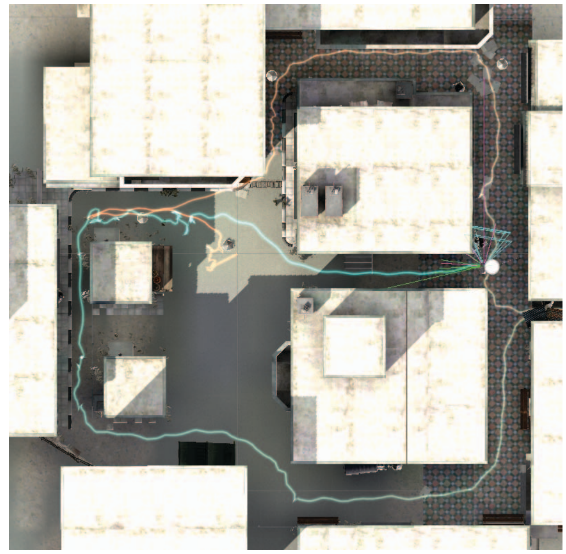

Figure 7: Top-down view of a user's walking path. Orange meaning old and Cyan meaning recent. Users would naturally avoid obstacles while they did not have any obstacles in the physical space. Lines are for the purpose of visualization and were not visible to users at the time of experiment.

To minimize direct interaction with users during the experiment and to make the experiment process more robust, we created a custom remote control web app that let the experimenters start the tutorial or the virtual scene from a distance or monitor the user in the virtual environment while simultaneously seeing them in the real space, helping the experiment run smoothly. The interface was implemented using Google's mobile platform Firebase and it relayed information like time, number of gems collected, and user location and orientation in each virtual environment to the experimenter. The app was built such that multiple instances could be run in any web browser with a key code. This helped us run and control parallel experiments using multiple devices in the same tracking space. The app recorded all user interactions including position, orientation and controller button clicks at 20Hz and saved it for future playback and analysis. An example of the user interaction playback can be seen in Figure 5.

The four views were rendered in Unity, with two indoor scenes and two outdoor scenes. Both pairs were similar in style and feel to make locomotion in them comparable but were different enough to avoid any learning effects (see Figure 2 and 5). Indoor scenes are two halves of the same scene[1] taken from the Matterport3D dataset [9]. The scenes were capped and edited in a 3D editing software to feel coherent to the users. We also removed steps and kept all the walkable surfaces flat. Outdoor scenes were made in Unity based on a designed map. All assets used to assemble the scene were downloaded from the Unity AssetStore. Assets were placed by hand around a pre-designed top-down map. precautions were taken to avoid using distinguishable assets like store signs in both scenes. this prevented creating identical areas and causing learning effects.

4.3 Procedure

We designed a within-subjects experiment and each participant did teleportation and walking during the experiment. They navigated through a total of six virtual scenes that consisted of one tutorial and two virtual environments per locomotion technique. Users were not allowed to walk through virtual walls and objects. Hence, they walked paths as one would in equivalent brick and mortar places (see Figure 7). They started with a tutorial for either teleportation or natural walking. Their first tutorial taught them how to collect gems and answer questions at the end of each locomotion condition. These user interactions were not recorded nor considered in the analysis. Participants were allowed to take as long as they wanted in answering the questions, both in the tutorial and the experiment conditions. However, the actual locomotion task was limited to 5 minutes for each condition. The 5 minute time was derived from the amount of time required to walk through both the indoor and outdoor virtual spaces as determined by our pilot study. Since we did not want to integrate any self-motion or virtual environment manipulations (see Section 2), the indoor sports arena was the right sized physical space to run the walking experiment. The goal was to ensure participants had enough time to walk through the virtual spaces at least once as that would be the bare minimum required to build a mental map of the space. The same amount of time was used for teleportation to make for equivalent comparison. While teleportation allowed for exploring the space much more quickly than walking, participants had enough time to move around the space multiple times, motivated by the gem collection task, to potentially overcome the limitation of path integration seen in teleportation techniques [2, 14].

During the walking condition, the experimenter used a tablet device that ran the custom remote control web app. This allowed the experimenter to follow from a short distance away what the participant saw and did. At the same time they were in a position to prevent the user from walking into the gym boundary in case of tracking failure. Over the course of the experiment, we had to intervene and restart the tracking system a total of three times during the 16x2 trials. With each trial lasting 5 minutes, that amounts to only three tracking failures in 160 minutes of VR walking. For these cases, we resumed the experiment by asking users to close their eyes while we restarted tracking by realigning a virtual and a real wall, before they continued the experiment.

Typical tasks used to assess cognitive map building include sketching a map of the environment or pointing to *non-visible landmarks* in the environment [20]. We used a pointing task for our assessment.

[1] Scene ID:ac26ZMwG7aT

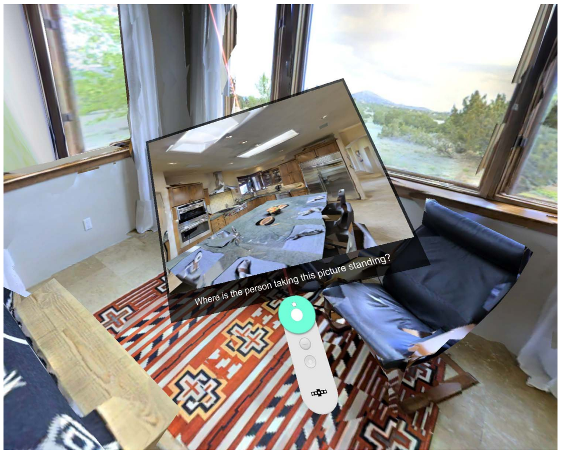

Figure 8: An example pointing task question. The participant was teleported to a specific spot in the scene and shown a picture of a target point in the scene not currently in view. They were expected to look around and point in the target direction.

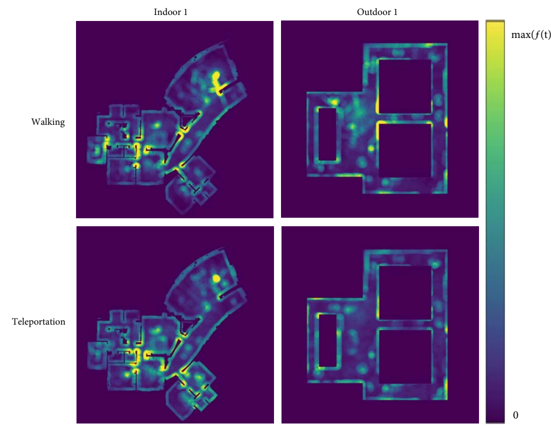

Figure 9: View Coverage map for 2 of 4 scenes in Teleportation vs Walking. View coverage is the accumulation of projected user's camera frustum on the 3D scene over time.

The tutorial was followed by the first scene that participants needed to explore, which was either an indoor or outdoor scene using either the natural walking or teleportation. After each scene, users were asked to complete a set of ten pointing tasks in VR (see Figure 8), fill the Slater-Usoh-Steed (SUS) [44] presence questionnaire, and the SSQ. Each locomotion technique was used in one outdoor and one indoor scene. The order of the trials was counter-balanced using a latin-square assignment by systematically varying the order in a full permutation which was 16. Participants were asked to collect 10 gems scattered throughout each virtual environment though only 8 were placed in each scene. This was done to encourage exploration. The gem placement was balanced across the scenes in count and findability. Participants collected a gem by pointing a virtual laser at a gem and clicking a button on the controller. After the study, participants filled out a custom questionnaire that asked about their preference for a locomotion technique and any additional comments they had about their experience.

4.4 Assessment

In order to analyze the effects of the different locomotion techniques on cognitive map building, participants had to complete a VR pointing task [3, 20]. We had asked participants to pay attention to the virtual world they were exploring and additionally encouraged exploration through the gem collection mechanics. Now, after each condition, we presented a series of ten VR pointing tasks to gauge their mental map building. The virtual space was something we expected them to have learned in the five minutes of exploration time as shown in our pilot study. At the end of the exploration time, we presented participants with pictures of one part of the virtual world (see Figure 8) and asked them to point to the spot they thought the person taking the picture had been standing when taking the picture. Using this metric, 0 degrees meant perfect estimation of the virtual photographer's location while 180 degrees was maximum error. The error was calculated on the 2D projection of the 3D aim vector onto the ground plane.

For each pointing question there was a possibility that user did not have the chance to see the space appearing in the question. Each question consisted of two parts: the location we teleported the user to, and the picture we showed them. We define "validity" for each question as follows: The question is valid if the user has seen both the location they are being teleported to, and the view they are being shown on their controller. In order to make sure we assessed the results for only the valid questions, we performed a measurement after the experiment using the recorded movement data. We checked for each frame if the user had had a direct line of sight with any question location and whether they had been within a threshold of three meters from that point. We also took the same steps for the location of the virtual camera that created the target view, plus checking if the user has had a similar angle view (angle difference threshold of 45 degrees). This ensured that the user had a chance to see the view depicted in the question. At any frame in which these values were true all at once for location or view, we considered that location or view "valid" and recorded it with a flag variable. When analyzing the data, we excluded the questions that did not have a valid flag for both location and view.

Participants were asked to stand and not move while answering the questions. Looking around was allowed and encouraged. Pointing to the target view locations from within the virtual environment required the participants to update their mental map of the virtual space with respect to each picture, especially because participants were moved to a different virtual location in the scene before each picture was shown. Having a mental map of a place implies knowing the relative placement of the various spaces. For example, at home, one is easily able to point to where the kitchen is when standing in a bedroom and vice versa.

5 Results

Our dependent variables included self-reported simulator sickness, self-reported presence, accuracy from post-trial pointing tasks, coverage of observed area, and finally, stated preference between locomotion methods.

We now report, in turn, on the results for each of these metrics.

5.1 Simulator Sickness

Before the first locomotion trial, we collected a simulator sickness baseline assessment from each participant, using the SSQ questionnaire.

From the questionnaire answers, we compute the four metrics of Nausea-related subscore (N), Oculomotor-related subscore (O), Disorientation-related subscore (D), and SSQ Total Score (Ts) according to the scoring functions in [22]. After exploring each scene, via either walking or teleportation, participants were asked to fill out the SSQ again. The average difference values to the baseline

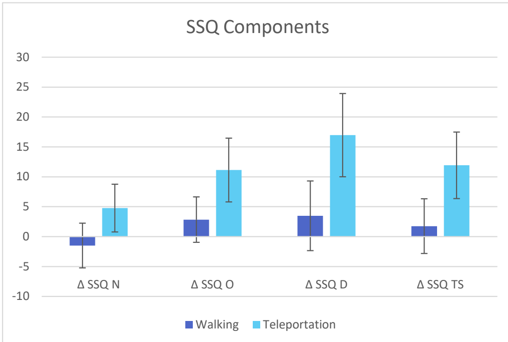

Figure 10: Mean values for SSQ Questionnaire components measured as deltas to a baseline condition before the start of the experiment, split by locomotion technique. Error bars depict standard error.

Table 1: Wilcoxon signed-rank test on Simulation Sickness components by Locomotion type (W for Walking and T for Teleportation). Listed are the Simulation Sickness medians, critical z, and p values. Participants experienced less simulation sickness while walking.

SSQ Component	M W	M T	z	p
Total Score	16.83	24.31	2.012	0.044
ΔTotal Score	1.75	11.92	2.012	0.044
ΔSSQ N	-1.49	4.77	2.055	0.040
ΔSSQ O	2.84	11.13	1.834	0.067
ΔSSQ D	3.48	16.96	1.965	0.049

for each of the four metrics, split up by locomotion technique, are summarized in Figure 10.

The distribution of these deltas not being Gaussian, as determined by a Shapiro-Wilk test of normality, we performed multiple Wilcoxon signed-rank tests on the four SSQ metrics to check for any statistically significant difference between teleportation and walking. There were significant differences between walking and teleportation for Total Score (Ts), Nausea-related subscore (N), and Disorientation-related subscore (D) (see Table 1 for medians, z, and p values), with walking leading to lower reported simulation sickness. The delta means in the Oculomotor-related subscore (O) were narrowly not significantly different between locomotion techniques ($p = 0.067$). However, teleportation did induce significantly higher delta SSQ Nausea (N) and Disorientation (D) subscores ($p = 0.04$ and $p = 0.049$ respectively), resulting in a significantly higher Total Score (Ts) than natural walking ($p = 0.044$).

These results confirm hypothesis H2 and even indicate higher overall simulator sickness for teleportation.

5.2 Presence

After experiencing each scene, via either walking or teleportation, participants were asked to fill out the Slater-Usoh-Steed (SUS) presence questionnaire. As suggested in [44], the SUS score was computed as the number of answers r out of n that have a score of ‘6’ or ‘7’ on the 1-7 Likert scale. We additionally report the average value of all SUS questions in Figure 11.

Results from a Wilcoxon signed-rank test show no significant difference in SUS score between the walking and teleportation conditions ($z = 1.653$, $p = 0.098$). A plot (Figure 11) and analysis of the raw averaged SUS questionnaire scores may however indicate a trend towards better self-reported presence for Walking: the averaged raw SUS questionnaire responses were significantly higher ($z = 2.534$, $p = 0.011$) for walking compared to teleportation (see Table 2).

Overall, these results provide some limited evidence for hypothesis H3, but additional studies are needed for a more clear confirmation.

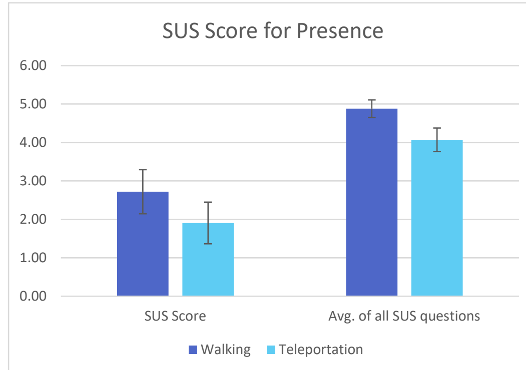

Figure 11: Mean values for differences in SUS Questionnaire, categorized by locomotion. Error bars depict standard error.

Table 2: Wilcoxon signed-rank test on overall averaged questionnaire score from the SUS Questionnaire by Locomotion type (W for Walking and T for Teleportation). Listed are the Presence medians, critical z, and p values.

Presence Component	M W	M T	z	p
SUS score	2.25	1.00	1.653	0.098
SUS Likert answer mean	4.53	4.00	2.534	0.011

5.3 Pointing Tasks

A Friedman test was run to determine if there were differences in Pointing task error in each of the four different scenes($\tilde{\chi}^2(2)$ = 16.200, p =0.001). Pairwise comparisons were performed with Bonferroni correction for multiple comparisons. Post-hoc analysis showed that effect of scene on the results from the aiming task is statistically significant. Pointing errors are significantly different between “Indoor 2” and “Indoor 1” (p = .006) and between “Indoor 2” and “Outdoor” 1(p = .006), indicating that in spite of our attempt to create two comparable versions each of indoor and outdoor scenes, one scene and/or pointing task quiz in particular (“Indoor 2”) was easier to make sense of and answer.

Walking users had a mean pointing error of 33.95° and teleportation users had a mean pointing error of 34.21°. Wilcoxon signed-rank tests showed no significant differences in pointing task error for walking vs. teleportation (see Table 3).

Table 3: Wilcoxon signed-rank test on effect of locomotion on pointing error. There was no significance between locomotion techniques.

Dependent Variable	M W	M T	z	p
Pointing Error	33.95°	34.21°	0.052	0.952

Table 4: Wilcoxon signed-rank test on our coverage factor by locomotion type (W for Walking and T for Teleportation). Listed are the coverage medians, critical z, and p values. Only scene ”Outdoor 1” showed significant difference.

Scene Coverage factor	M W	M T	z	p
Indoor 1	0.0208	0.0208	2.012	0.674
Indoor 2	0.0199	0.0196	2.012	0.208
Outdoor 1	0.0243	0.0225	2.055	0.012
Outdoor 2	0.0241	0.0253	1.834	0.327

5.4 Coverage of Virtual Scene

We calculated view coverage using the collected interaction playback after the experiment by casting 20 rays at 0.1 second intervals from eye to the scene. We placed a particle where the ray hit the scene and then divided the covered area by the total visible area of each environment. The resulting metric was consistent among all users and provided a measure for coverage. A significant view coverage difference according to a Wilcoxon signed-rank test of coverage percentages between the walking and teleportation conditions is only evident for Scene ”Outdoor 1”, with the walking condition producing significantly higher coverage for that scene (see Table 4 and Figure 9). Wilcoxon signed-rank tests did not show any significance in difference of coverage for Teleportation vs. Walking for the rest of the scenes.

The combined results on pointing tasks and virtual scene coverage do not either confirm or reject hypothesis H1. However, it is noteworthy that both techniques enabled participants to perform comparatively well on the pointing tasks (average of 34 degrees error, with 3 degree standard error). Likely, the 5 minutes exploration time gave plenty of opportunity for either locomotion technique to form reasonable mental maps. It is interesting that in spite of an overall speed advantage for teleportation, the only significance in difference of view coverage comes in favor of real walking.

5.5 Participant Preference

In the post study survey, none of the participants reported a preference for teleportation over walking: 15 preferred walking, 1 did not answer. On the question ”Which movement method did you find easier to use?”, ten participants chose walking and five users chose teleportation (see Figure 12).

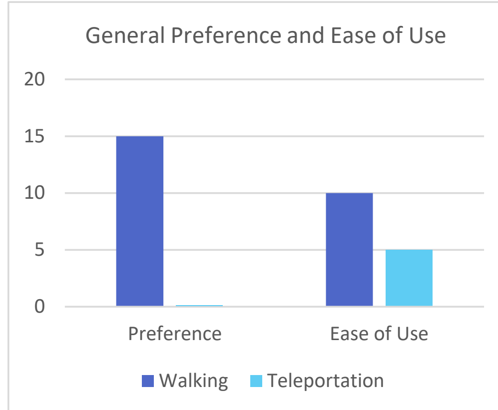

Figure 12: Number of responses choosing Walking or Teleportation respectively for overall Preference and Ease of Use. Walking was the preferred method among all the participants. Ten users considered walking easier to use than Teleportation (one abstaining).

6 Discussion

The results of our user experiment comparing two VR locomotion techniques for exploring indoor and outdoor virtual environments indicate an overall clear winner and many interesting discussion points. Natural walking was almost universally preferred over teleportation for navigating the house and an urban market environment. This was despite the large amount of walking participants did in the indoor sports arena. Teleportation led to significantly higher self-reported disorientation, nausea, and, consequently, total score components of the SSQ, and we observed a trend towards higher self-reported presence for natural walking.

While we did not find prior work that compares natural walking directly with teleportation, teleportation has been compared with joystick control [7, 23] and redirected walking [23] in smaller environments. In both these studies, teleportation caused less nausea than joystick and was preferred over joystick. It was comparable to redirected walking in terms of user preference [23] and there was no significant difference in presence between teleportation and leaning [7]. Our results showing teleportation to cause higher disorientation is thus, slightly unexpected, though unlike prior work our comparison is with natural walking in a large space. In what might be perceived as a diverging finding, Suma et al. [40] showed walking to cause higher nausea, occulomotor discomfort, and disorientation compared to a simulated walking technique in a virtual maze, which they described as a “navigationally complex environment.” Participants in our study walked in natural environments such as a single-family home and an outdoor market. While the virtual environments are not directly comparable, we believe advances in VR hardware technology may explain the different outcome for walking in our work versus the study by Suma et al. [40].

Previous research demonstrated benefits of real walking compared to more indirect and passive locomotion techniques mostly for smaller virtual environments, but for larger scale scenes there was a real possibility that improved speed and flexibility of a ’supernatural’ technique such as teleportation, could yield some benefits for wayfinding and survey knowledge acquisition. At the same time, teleportation is a technique that is widely used in VR games, and reported presence also point towards natural walking as being preferable.

It was clear to us experimenters, both from the design of the methods and from observations of our users during the trials, whose paths through the various environments we could follow in real time through our monitoring app, that teleporting afforded faster navigation than natural walking, as participants could jump to any visible part of the scene in one fell swoop. However, since they had to collect gems, they needed to build a mental map of the respective environment in keep track of spaces they had already visited and collected a gem from versus other spaces. In fact, for one of our four scenes (Outdoor 1), Walking resulted in significant higher view coverage of the space within the 5 minute exploration. We interpret this to mean that while teleportation has the inherent ability to enable faster movement in the virtual space, it does not necessarily mean user’s always use it in quick succession. It is possible that other tasks (such as, e.g., path-oriented wayfinding in non-convoluted environments) would better bring out advantages of teleportation.

Overall, our results do not present any absolute red flags for the teleportation method. Some participants reported teleportation as easier to use (possibly alluding to less physical effort needed). While there were significant differences in self-reported simulator sickness deltas, overall symptom scores remained low for both conditions. It is worthwhile to point out that according to our results, eye-strain is not at the root of the increased simulator sickness for teleporting, as the O score (Oculomotor-related subscore) deltas were not significant. The Nausea-related subscore (N) was a main contributor and the Disorientation-related subscore (D) may have contributed as well. It is possible that using a different implementation of teleportation like Dash [2] may have helped reduce the Disorientation-related subscore (D).

The results revealed some significant effects of the locomotion technique on cognitive map building. Regarding the pointing task and scene coverage percentages, there were some differences between techniques, again slightly favoring walking. This suggests that the choice between the locomotion techniques may impact mental map making ability. Even though people start making a mental map of a new place as soon as they arrive there [24], we encouraged exploration of the space through the collectible mechanic and participants were compelled to view the same places multiple times as they searched for the gems. This may have helped improve overall ability for both conditions.

7 Conclusion

As standalone VR headsets are now able, through inside-out world tracking, to track user pose in large physical spaces, new possibilities arise for mixed reality experiences that involve significant amounts of real walking. Few user studies exist that evaluate natural walking in virtual environments over such large areas as soccer fields or sports arenas.

We designed an experiment to test and compare natural walking and teleportation as two main types of locomotion for sports-arena-sized virtual environments, and our results indicate decided advantages of natural walking over teleportation in such larger environments in terms of user preference, induced disorientation, and some other metrics, including an observed trend towards higher presence and some isolated indications of better mental map formation.

Overall, this suggests that walking-based VR (or more immersive AR) in wide-area environments can become feasible and attractive for general audiences. Several technological advancements would be required to fully enable the educational and entertainment possibilities sketched in our introduction. Tracking would need to be more robust to challenging and varying indoor and outdoor conditions as our attempts to run this user study outdoors or within a completely unprepared sports arena were not successful. Headsets would need to be further miniaturized and their display capabilities expanded for comfortable immersion over extended periods of time along with the ability to seamlessly transition between AR and VR modes. For safe unattended VR walking, the user would need awareness of the physical world while maintaining immersion in VR as demonstrated by our design prototype from Section 3. Battery life and heat optimization would have to be improved, and the use of headsets in direct sunlight would need to be made effective and safe. But even in the absence of the technological breakthroughs needed for truly robust real-world implementations of wide-area VR walking, our work demonstrates that we can already define and successfully evaluate user experiences in this domain.

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